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Analysis of crush resistance and Mississippi-sourced sands to determine potential as proppant sands

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ANALYSIS OF CRUSH RESISTANCE AND MISSISSIPPI-SOURCED SANDS TO DETERMINE POTENTIAL AS PROPPANT SANDS

By:
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A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

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Approved by

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Reader:	Dr. Gregory Easson

DEDICATION

To my parents, thank you for supporting me for all these years and believing in me even when I could not.

ACKNOWLEDGMENTS

To my advisor Dr. Lance Yarbrough, thank you for your support and encouragement these past two and a half years. You have always expressed encouragement and positivity in the face of countless obstacles: changing thesis topics completely, the delayed arrival of the crushing machine and then the rush order for an adapter for that same machine, getting the crush cell good and stuck on that trial crush test, having to re-mill the crush cell after getting it stuck again, and so very many more. Words cannot fully express the extent of my gratitude to you, sir, but I thank you anyway.

Paul Matthew Lowe, thank you for all of the work you did getting the crush cell ready for us. We sent it to you more than a few times, and I am extremely grateful you were very quick to repair it each time.

I would also like to acknowledge Dr. Gregory Easson and the Mississippi Minerals Resource Institute. Thank you for contributing your sand samples for this study. Without them, this thesis would not have been possible.

Thank you to Ms. Jennifer Parsons, Dr. John Samonds, and the entire Sally McDonnell Barksdale Honors College. You have been by my side from the beginning. You have talked me through various anxieties at different stages of my college career every year ever since I was a freshman. You have seen me at my highest and my lowest, but you never once gave up on me. Thank you.

ABSTRACT

Proppant is a media used in hydraulic fracturing to bear in-situ stresses in order to maintain fracture networks, which act as highly permeable pathways for hydrocarbon recovery. Proppant can be made from a variety of materials such as glass, ceramic beads, sand particles, and more. Proppants are characterized by their size, sorting, roundness, and sphericity. These properties help determine the compressive strength of the pack proppant. This study focuses on these properties for natural sand. The purpose of this study is to evaluate the viability of lower-quality sands as proppant sands by testing the affect these properties have on the compressive strengths of each sample. Testing is in accordance with ISO 13503-2 (2006) and ISO 13503-2 Amendment 1 (2009). These standards state that sands used as proppant should generate no more than 10% fines during crush tests.

This study tested five sand samples: one commercial-grade proppant, two Mississippi-sourced sands, one recreational sand, and one composite sample made from two previously tested samples. This study found that sand particles are more prone to generating fines if they are coarser and more angular, but the sub-angular specimen did meet strength requirements at lower stresses. This study also found success mixing two proppants to create a proppant that generated fewer fines than either of its parent sands. Mica grains in one of the Mississippi-sourced sands affected the compressive strength of the sample. Anomalous fine generation curves occurred for multiple sands, showing decreasing fine generation at increased stresses, and may be attributed to testing

complications. Expanded study to reproduce and verify results is recommended, as well as removing mica from samples in future studies.

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1.0 INTRODUCTION

1.1 Background

A common method petroleum and natural gas industries use to stimulate reservoirs for recovering hydrocarbons is hydraulic fracturing. This is performed when highly pressurized fracturing fluids are injected into the subsurface to create or open preexisting pathways for the hydrocarbons to flow through to the surface of the well. Oftentimes, fracturing fluids contain proppants, which are natural or man-made media that bear in-situ stresses and prevent induced fractures from closing (Veatch, 1983; Man and Wong, 2017). By maintaining fracture integrity, proppants become permeable pathways that allow fracturing fluids easier access to targeted formations.

Proppant comes in a variety of types: industrial sand, manufactured ceramic beads, resin-coated media, and more. Proppant types are further distinguished by their mechanical properties and shapes. Common properties used to characterize proppant include compressive strength, sphericity, roundness, and a range of mesh sizes for 90% of the pack grains.

Proppant type and particle size directly relate to crush resistance. Smaller particles tend to have higher crushing strengths than larger particles, but larger particles are thought to produce larger fractures (Zheng, 2017; Tang et al., 2018). Some studies have found success in mixing sizes of proppant to create better fracture networks than ones formed using uniform proppant size; however, adding smaller particles decreases the void ratio, thereby reducing permeability and overall fracture conductivity (Guo et al., 2012; Zheng, 2017). Proppant strength is an important property not only because it determines how much pressure the proppant pack can withstand, but also because higher strength proppants are more resistant to crushing, thereby producing fewer fines (Tang et al., 2018). Fines generation can negatively impact productivity because fines clog pore space and reduce permeability and the productivity of the well. Studies have found that only 5% fines can reduce the conductivity of the proppant pack by more than 50% (Lacy et al., 1998; Zheng, 2017). Therefore, a proppant is assigned a crush classification dependent on the greatest amount of stress it can withstand without generating fines in excess of 10% of the proppant pack volume (ISO, 2009).

Sphericity and roundness are also important properties because they affect grain packing. It is widely agreed that round and spherical proppants give greater pack permeability than angular- or irregularly-shaped proppants. Furthermore, rounded grains can be transported more easily than angular grains. This is most important for use as proppant because rounded grains travel longer distances and extend deeper into fracture networks, allowing for greater well productivity. Proppant sands should have both an average sphericity and an average roundness of 0.6 or greater (ISO, 2009).

For this study, we focused only on natural sand proppants, also known as fracking sand or frac sand. Natural sand is advantageous because it easy to obtain and therefore relatively cheap. It also has a fairly low specific gravity which allows it to travel further along the fracturing fluid before settling, thereby creating larger fractures than denser alternatives (Lacy et al., 1998; Tang et al., 2018). The drawbacks of natural sand proppant are that it is not as strong as manufactured proppant, meaning that natural sand proppants generally break at lower pressures. It is also more susceptible to crushing and fine generation than reinforced proppants. Lastly, the natural formation of sand increases the uncertainty of its composition and properties (Liang et al., 2016).

1.2 Objectives

The purpose of this study is to test how roundness, sphericity, and sorting affect the crush strength of proppant sands. We have gathered a collection of proppant sands, commercial sands, and Mississippi-sourced sands for testing. Descriptions of theses sands are located in Appendix A. Our goals are to discern if there is a link between a sand's compressive strength capacity and the roundness of its grains, to assess the crush strength of a Mississippi-sourced sand as a potential proppant, and to determine if a mixture of two different proppants affects crush resistance. Insight into these properties will promote more efficient fracturing, increasing oil production by reducing permeability loss and increasing the yield of usable sands for mining operations of frac sand.

2.0 METHODS

2.1 Testing Procedure—ISO

This study was performed in accordance with ISO 13503-2 and ISO 13503-2/Amendment 1. This standard and amendment details procedures to evaluate potential proppant media by testing their physical properties. General sampling procedures required us to reduce samples using a sample splitter to maintain representative samples. The sample splitter helped to reduce the degree of particle segregation within the samples, and the reduced samples were then used for sieve analyses. ISO suggests that a minimum of seven sieves, decreasing in sieve opening, should be used along with a catch pan and cover. We initially used 12 sieves, ranging from sieve #10 to #200, but we later reduced that number to 11 sieves.

The sieve analyses provided grain size distributions for each sample. Industrial proppants generally have at least 90% of their grains fall within the range of a primary and secondary sieve. The primary sieve is the coarser sieve, and the secondary is the finer. Proppant pack sizes are typically listed as this range of sieve size. The ISO manual lists some typical size designations, such as 40/70 and 70/140. We evaluated each sample's potential as proppant prior to testing by comparing the results of the grain size distribution to the typical values listed in the manual.

Individual grains were studied to determine proppant shape prior to the crush tests. Referring to a Krumbien/Sloss chart provided in the ISO manual (2006) (Figure 1), we determined particle sphericity and roundness using photomicrographs (Figure 2). These values are listed in Table 1. Industrial sand proppants should have an average of 0.6 or greater for both roundness and sphericity (ISO, 2009).

Standard crush stress-level guidelines for frac sand proppants used to be evaluated from a minimum of 2000 psi to a maximum of 5000 psi, but now proppants are evaluated at increasingly high stresses until they pass the 10% threshold for fine generation (ISO, 2006; ISO, 2009). We crushed our proppants at intervals of 1000 psi, starting from approximately 4000 psi and ending around 8000 psi. The crush tests were performed by Dr. Yarbrough using a crush cell (Figure 3) which was manufactured on the campus of the University of Mississippi to the dimensions specified in the ISO manual. We performed another sieve analysis on each crushed sample and recorded the data on grain size distribution curves (Appendix B).

2.2 Testing Modifications

There were some tests in the ISO manual we chose to not perform because they did not further our study focus. Testing for acid solubility, turbidity, densities, and the loss on ignitions was outside of the scope of this study.

Of the tests we performed, there were some instances where we deviated from the ISO procedure. During the sieve analysis, it is standard practice to sieve from 80 g up to 120 g of a sample in a sieve shaker for a minimum of 10 minutes. We ran the samples through the sieve shaker for six minutes, and most of our samples were in excess of 120 g. Of all the crushed samples sieved, only one had a starting mass greater than 130 g. Original samples used to determine initial grain size distribution ranged in mass from 100 g to 800 g.

Another modification pertained to sample preparation prior to the crush test. Standard procedure is to reduce samples into particles sized between the primary and secondary sieves. Fine generation is then determined by the percent of fines that pass the secondary sieve. We elected to not sieve our samples because we wanted to test how sorting affected the compressive strength of each sample. We determined the amount of fines generated by using the increase of percent passing sieve #100 from the grain size distribution analyses' (Figures 4 and 5).

We discovered one complication during the sieve analyses of the crushed samples and had to reduce the number of sieves used from 12 to 11. Sieves #50 and #70 had previously retained some chemical damage from a different project but were initially still usable; however, the multitude of sieve analyses wore away at the weak points and opened holes in the sieve mesh. As a result, there are some sharp increases on the grain size distribution curves (Figures 6-10) where grains accumulated in sieve #80. We were able to replace sieve #50 with another, but we could not find a replacement for sieve #70.

More modifications were required to perform the crush tests. Our compression machine was hand-operated, and we had to manually release the stress after we reached our target force. As a result, some of our stress readings are slightly above or below the targeted stress levels. Furthermore, the ISO manual said to hold the target stress for 2 minutes, but the compression system did not allow for maintained applied stress.

2.3 Mixing Proppant

We created a mix of one proppant sand by combining equal parts from two of our industrial proppants. We used the Ottawa proppant sand and the Mississippi proppant sand to create what will henceforth be referred to as the 50-50 Blend. Using a split sampler, we reduced the original samples to a little over 300 g each. Then we combined the two samples and split the mixture into five smaller samples. We crushed the 50-50 Blend samples under the same conditions as the other samples, starting from 4000 psi.

3.0 RESULTS

We analyzed eight different sand samples: four locally-mined sands from Mississippi, three industrial proppant sands, and one recreational-use “play sand.” We assigned a degree of sphericity and roundness for the four locally-mined sands and two of the proppant sands (Table 1) by comparing a Krumbien/Sloss Chart (Figure 1) to the photomicrograph for each respective sample (Figure 2). We selected four of those samples to undergo crush testing at five different pressures, and we created one 50-50 composite sample using two of the four selected samples. The crush cell was mined to ISO specifications on the University of Mississippi's Oxford campus (Figure 3).

Crush results are graphically represented in two ways. The first graph displays total amount of fines passing sieve #100 under applied stress (Figure 4); the second graph displays the net change of fines passing sieve #100 under applied stress (Figure 5).

The Ottawa proppant sand is a clean, white quartz sand that is well-rounded and well-sorted. This sand had the fewest fines passing sieve #100 for all stresses. There was a less than 1% increase in fines from the starting sample to the lowest applied stress. As the applied stress increases from 3998 psi to 6992 psi, fine generation increases linearly before leveling out as the stress increases to 8002 psi. A more detailed display of fine generation from this sample can be seen in Figure 6. Fine generation increases for every increase in pressure. The maximum percentage of fines passing sieve #100 is less than 10%.

The Mississippi proppant sand is a very pale brown, clean quartz sand with a high sphericity and roundness (Table 1). Approximately 75% of the grains are retained in sieves 70/140. Although the Mississippi proppant had the highest percent of fines generated relative to total sample volume (Figure 4), it did not have the greatest amount of fines increase under pressure (Figure 5). There was a drop in fines produced from the original sample's 36.5% to the crushed sample's 30.7% for 4002 psi. Then, there is a sharp increase as the stress increases to 5017 psi, and the amount of generated fines is slightly surpasses the uncrushed sample's amount. As the applied stress increases, there is a gentle rise in the amount of fines before it levels out. The peak applied stress at 8001 psi has a slightly lower amount of fines produced than the previous stress had at 6998 psi.

The unusual drop in fines produced is further illustrated by Figure 7 which displays the sieve analyses for this sample at all pressures. It shows that there is a large difference in fines passing for almost every sieve from the samples with the lowest two pressures (0 psi and 4000 psi) to the rest of the samples. Although the uncrushed sample has the highest amount of fines produced for all sieves, the 4000 psi sample does begin to align more with the other samples as it approaches sieve #100.

The 50-50 Blend had the third highest amount of fines produced for total volume (Figure 4) and is the sand with the lowest amount of net fines produced (Figure 5). It was made from the high-performing Ottawa proppant and the low-performing Mississippi proppant. There is no data preceding 4000 psi for this sample because we did not run a sieve analysis on it prior to administering the crush tests. Similar to the Mississippi proppant, the 50-50 Blend had a cyclic trend for fine production. The lowest applied stress had a fairly moderate amount of fines generated followed by a 3% drop. Then there was a nearly 6% rise in production followed by another drop of 1.7%. The next and final applied stress had a 1% increase in fines. The sample tested at 5000 psi had the lowest amount of fines for all sieves, and the 6017 psi sample had the highest (Figure 8).

We used a recreational-use Quikrete sand for our angular sand. It is a tan, poorly sorted quartz sand. This sand had the second fewest amount of fines passing sieve 100 (Figure 4) and the second highest amount of fine generation (Figure 5). It had a fairly linear rise in fines produced from the zero applied stress to 5017 psi. Then there was a slight drop in fine production for 6008 psi followed by another rise as stress approaches 8049 psi. The second rise is slightly less steep than the first. Figure 9 illustrates the significant increase in fine production for all sieves from the uncrushed sample to the first crushed sample.

We chose MONR-004 for our Mississippi-sourced sand. This sand was very fine, subangular, and micaceous. This sand had the second highest amount of fines passing sieve #100 (Figure 4) and the highest amount of net fines produced (Figure 5). It had an almost linear increase of fines produced from the uncrushed sample up to 6015 psi before nearly tripling its production rate as stress levels increased to 7003 psi. Fine production leveled out as we applied more compressive stress. Figure 10 displays the sieve analyses for this sample.

Details of the sieve analyses and associated grain size distribution charts for the uncrushed samples are located in Appendix C.

4.0 DISCUSSION

4.1 Analysis of Results

Of the four Mississippi-sourced sands, we chose to test MONR-004. Though WINS-002 had the highest degree of roundness (Table 1), it was also one of the poorer sorted samples. MONR-004 and NOXU-001 had the same degrees of both roundness and sphericity, but MONR-004 had the better sorting. MONT-005 was not considered because it had the lowest degrees of roundness and sphericity.

The Ottawa sand was the commercial-grade sample we tested, containing the best sorting, roundness, and sphericity for hydraulic fracturing activities. The results of the crush tests show the merit of these properties; this sample had the fewest fines generated at stress and had the second lowest amount of net fines passing sieve #100. Fine generation leveled off just under 7%, thereby qualifying for proppant-use according to the ISO standard.

The Mississippi proppant also met ISO requirements for use as proppant. Compared to the other crushed samples, it had the highest concentration of fines passing sieve #100 at 0 psi; however, the Mississippi proppant only generated 9.7% fines more than the lowest amount of fines it produced. Despite expecting this high performance, these results are suspect because there was a generous decrease in the amount of fines produced from the uncrushed sample to the first crushed sample. Some of this drop might have been caused by problems in the initial sieve analysis. The original sample was 105g so it was within the ISO-mandated size standards, but an additional four minutes in the sieve shaker might have sorted more fines past sieve #100.

The 50-50 Blend was created from the sand with the fewest fines passing sieve #100 and from the sand with the most fines passing sieve #100; as expected, this sample’s fines production is the median sample, and it met the ISO criterion for use as proppant. Unexpectedly, this sample also contained the fewest amount of net fines produced, performing better than its two parent samples and coming in with 5.8% fines produced. This corroborates with previous studies that found increased crush resistance mixing proppants (Guo et al., 2012; Zheng, 2017).

The angular sand exceeded 10% fines when tested at 5017 psi, exceeding the fine generation for most of the other samples. This was expected considering that this sample was coarser than the others and more angular, both properties reducing compressive strength. Technically, this sand did meet ISO strength requirements for use up to 4004 psi by producing fewer than 10% fines, but it still would not be suitable for hydraulic fracturing due to its particle shape which would not travel deeply within rock formations through fracture networks.

MONR-004 was the lowest-performing sample, generating the most fines. It behaved similarly to the angular sand until the applied stress increased to 5027 psi, following which the fine generation rapidly increased before leveling off. Part of this sample's weak compressive strength can be attributed to the mica grains present; the angularity of the grains are likely another factor. However, even with the mica present, this sample met ISO requirements for the lowest two applied stresses. It is highly likely that, upon removal of the mica, this sand would be applicable as a proppant for even greater stresses despite being sub-angular. However, despite meeting strength requirements, this sand is fine to very-fine, and further tests would need to be run to determine how that affects proppant pack permeability.

We expected to see the sands' fine productions increase for the entirety of the tests with some plateaus representing compaction and crush thresholds; however, the graphs showing fine production were unusual in that they contained significant decreases in fine production at higher stresses. Furthermore, this occurred for more than one sand, affecting the Mississippi proppant, the 50-50 Blend, and the angular sand.

These drops were contradictory to our expectations and could have occurred due to deviations from the International Standard. The most likely sources of introduced error are complications during either the sieving processes or the crush tests. The sieving might have introduced some error because the timing was 4 minutes less than the ISO standard. Post-crush samples generally contained an increased amount of fines per total volume and would need to be sieved longer to be certain of this. Some error may have been introduced during the crush tests because complications with the compression machine necessitated Dr. Yarbrough to administer the tests by hand. The sand packs were not all crushed at the same uniform speed, but it is unlikely that this caused issue with our results. Although the rate at which stress is applied to an object affects how it deforms—for example, fractures form to a higher degree in short-term tests than they do at the same pressure during long-term tests—both the administered crush tests and hydraulic fracturing use high pressures in short-term intervals. The most likely explanation for the anomalous drops in fine production is because we were unable to maintain stress values at targeted levels for the required 2 minutes. Sustaining targeted stress levels for additional time would have ensured each sample achieved its maximum crush threshold for each test, and there would have been no unanticipated drops in fine production at higher stresses.

Another possible source of error is that we had a fresh sample to crush for each test. Although ISO 13503-2 does not require reusing samples from lower crush tests at higher stresses, the decrease in fine productions may have been avoided if we had. As previously stated, we cannot say for certain that each subsequent crush test was performed under the exact same conditions as the preceding, and we did not definitively crush each sample to its maximum threshold before increasing the applied stress. Sand actively being used in hydraulic fracturing will retain all of the previous deformations retained at lower in-situ pressures, but this is not necessarily represented in our crush tests. This may have led to differential crush patterns and explains why some samples had a higher amount of fines at lower stresses. Tracking the stress-strain response of each test might also serve to explain this phenomenon.

4.2 Recommendations

While this study did provide some insight into the relationship between compressive strength and grain size, sorting, and roundness, it could be improved. First, all of the local Mississippi sands contained mica, reducing the overall compressive strengths of the samples. We kept bagged samples for each sieve size from the sieve analyses of the original, uncrushed samples. We found mica grains continuing throughout each sieve, but the fragments did appear to reduce in percent volume as the samples became finer. Companies wishing to use these sands as proppant will need to sieve the samples down to the desired primary and secondary sieves, and then they might chemically separate and remove as much mica as possible using flotation.

Future work could incorporate tests to determine permeability and conductivity. This could be accomplished by studying how crush tests affect not only grain size distribution, but also how it affects grain shape and grain packing and then quantifying how that affects void space and porosity. Furthermore, we only tested dry mechanical properties of the samples, but real world hydraulic fracturing often uses fluids. We cannot truly determine the effectiveness of these samples as general proppants until we test how they react when mixed with fluids.

We found success in reducing fine generation with our 50-50 Blend. Further studies could test strength capacity to determine the best ratios of high quality sands to lower quality sands, determining the most cost-effective combinations that meet ISO strength requirements.

5.0 SUMMARY

Our purpose for this study was to assess the compressive strength parameters of a variety of proppant sands and potential proppant sands using the standards set in ISO 13503-2 and ISO 13503-2/Amd.1. We studied eight different sand samples and chose four samples to test. We tested an additional sample that we created from two of those four samples.

We know that round and spherical grains are important for proppant because rounder grains are more efficient at maintaining fracture integrity, but does roundness or sorting affect a proppant pack's strength capacity? This study found that angular grains are more prone to generate fines than rounded grains, but sand grains with a lower degree of angularity can meet ISO strength requirements for hydraulic fracturing purposes that must withstand in-situ stresses up to 5000 psi. These sands are highly likely of withstanding greater stresses if they are clean sands, removing any present minerals which might reduce compressive strength capacity of the whole pack. Strength capacity can be increased and fine generation can be further reduced by creating a blend of high quality and lower quality sands, as we did with the 50-50 Blend.

There were some complications administering the crush tests, resulting in anomalous responses on our fine generation curves. This study should be repeated with corrections for testing issues and to verify results.

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Tables

Sample	Sphericity	Roundness
MS-Proppant	0.9	0.7
MO-Proppant	0.9	0.9
MONR-004	0.7	0.3
MONT-05	0.5	0.1
NOXU-001	0.7	0.3
WINS-002	0.7	0.5

Table 1. Krumbien/Sloss results

Figures

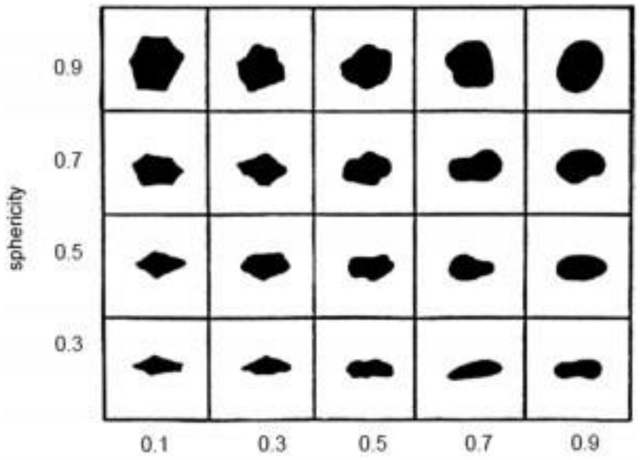

Figure 1. Krumbein/Sloss Chart (ISO, 2006)

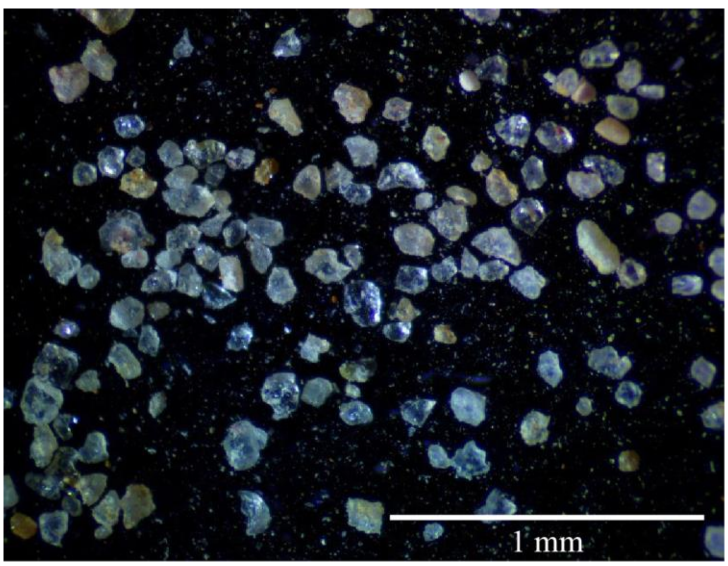

Figure 2a. MONR-004 photomicrograph

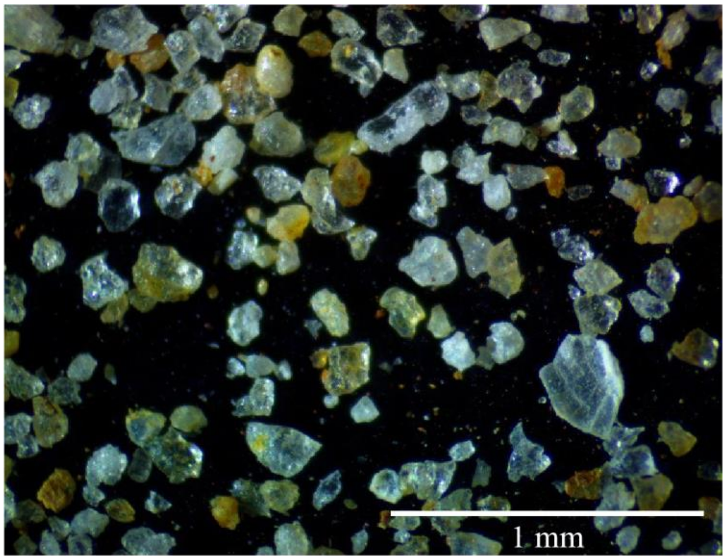

Figure 2b. MONT-005 photomicrograph

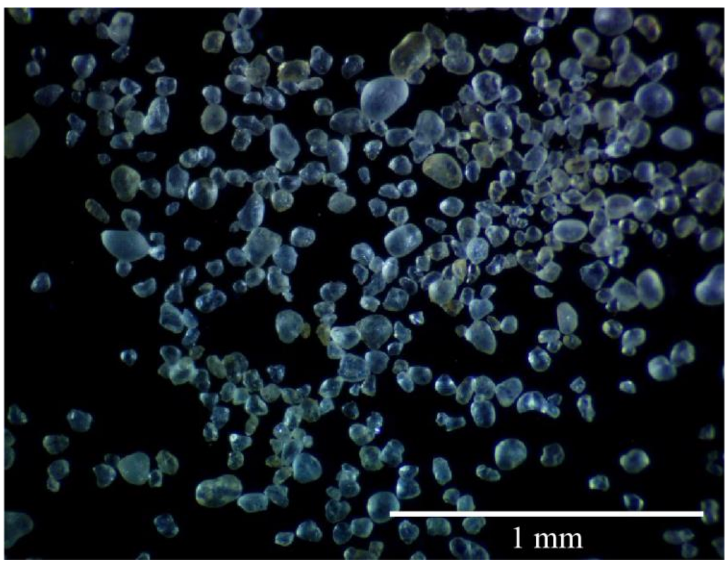

Figure 2c. Missouri proppant photomicrograph

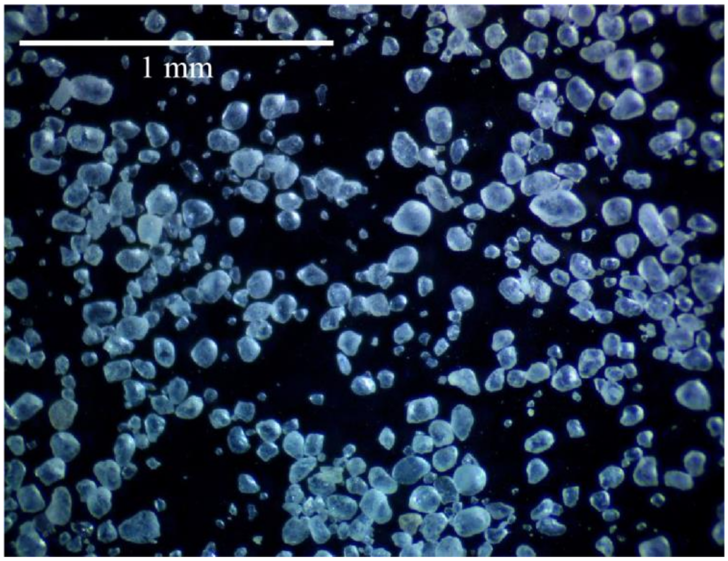

Figure 2d. Mississippi proppant photomicrograph

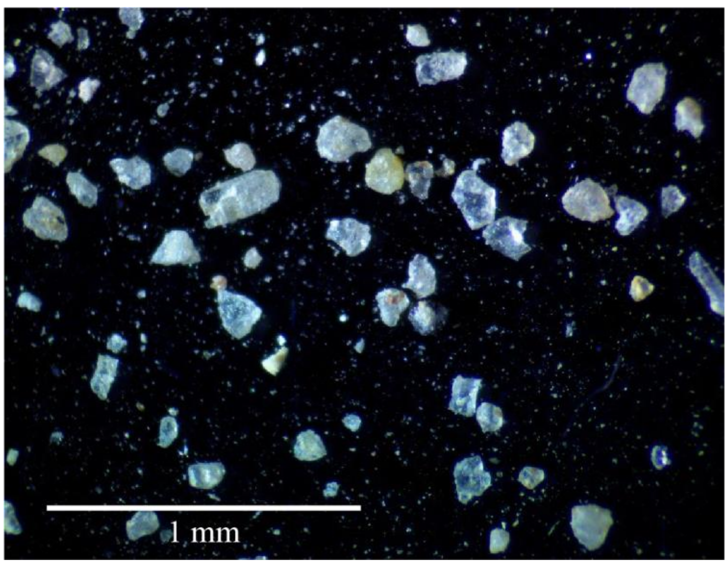

Figure 2e. NOXU-001 photomicrograph

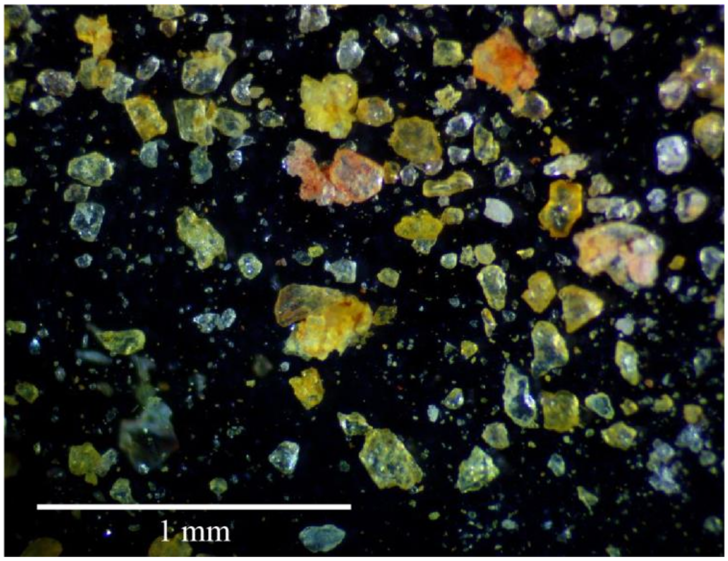

Figure 2f. WINS-002 photomicrograph


Figure 3. Crush cell

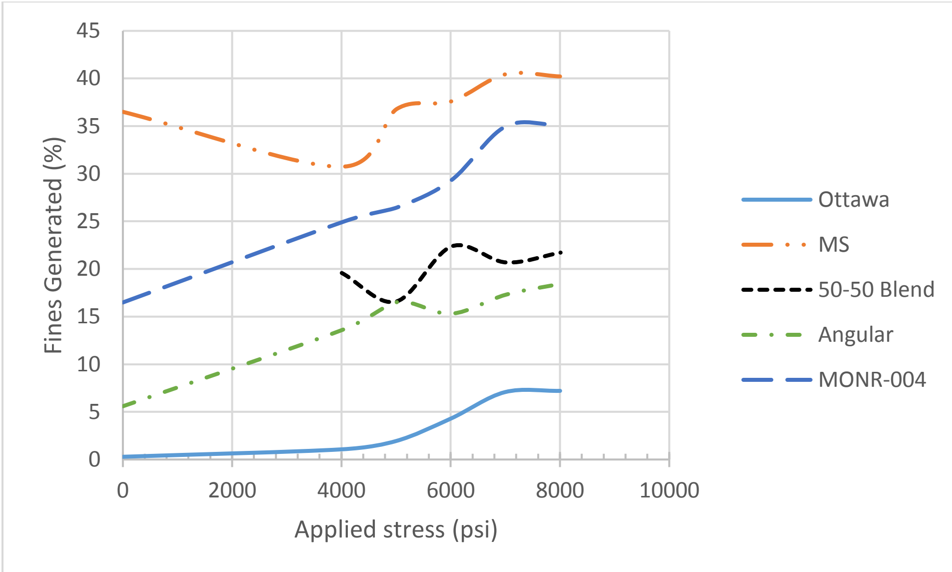

Figure 4. Fines generated passing sieve #100

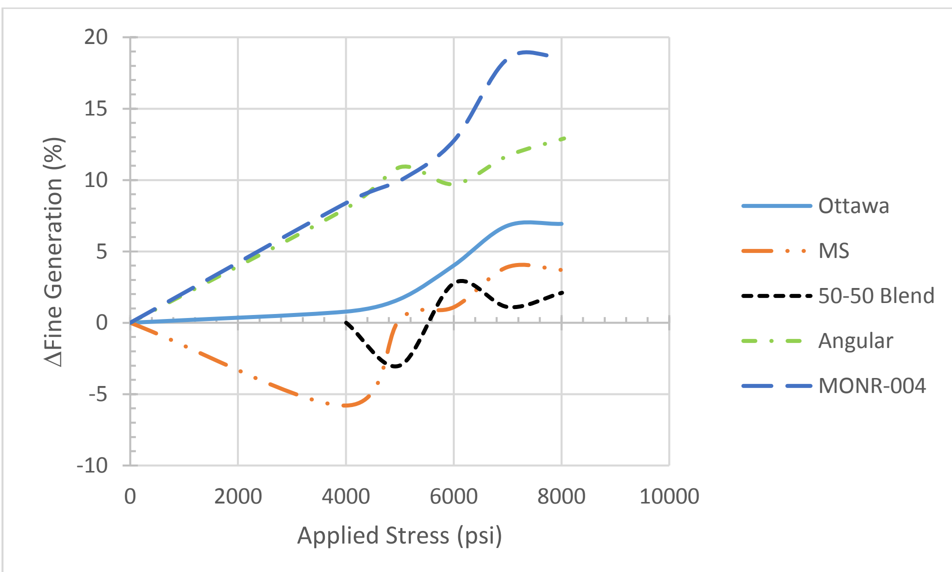

Figure 5. Change in fines generated passing sieve #100

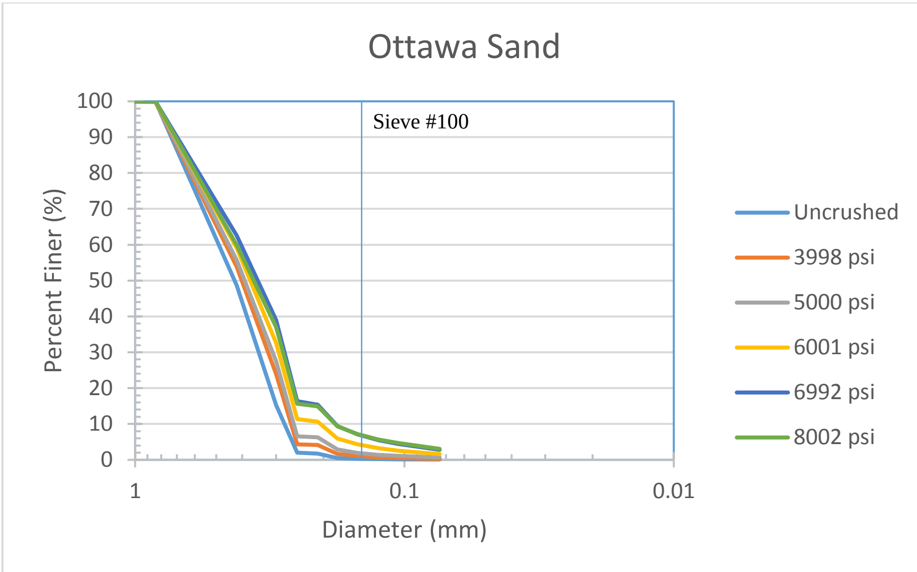

Figure 6a. Ottawa sand sieve analysis

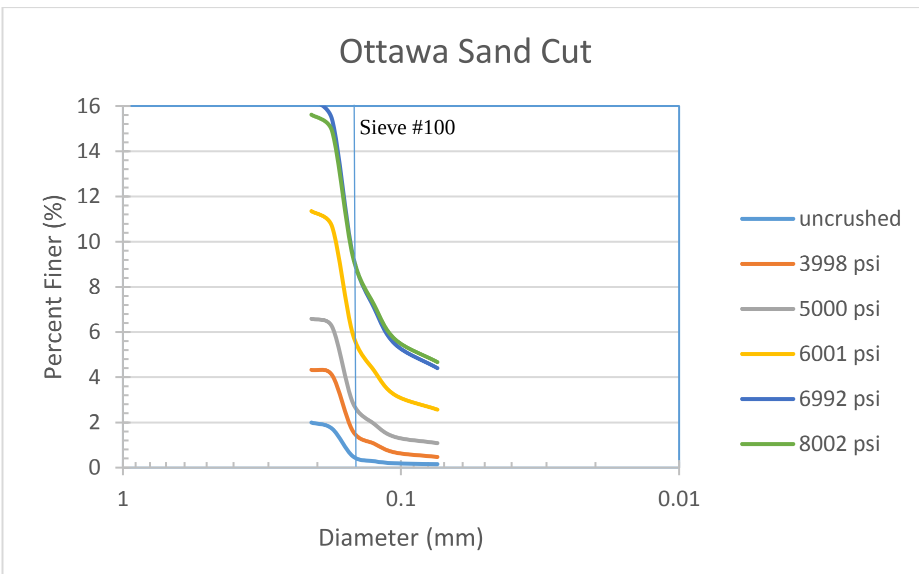

Figure 6b. Ottawa sand sieve analysis cut (sieves 60-200)

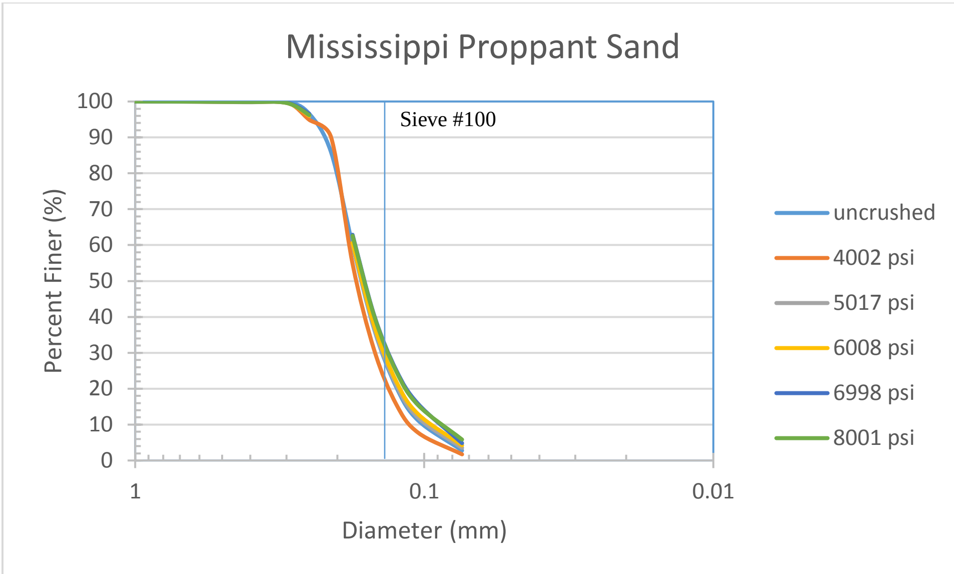

Figure 7a. Mississippi proppant sand sieve analysis

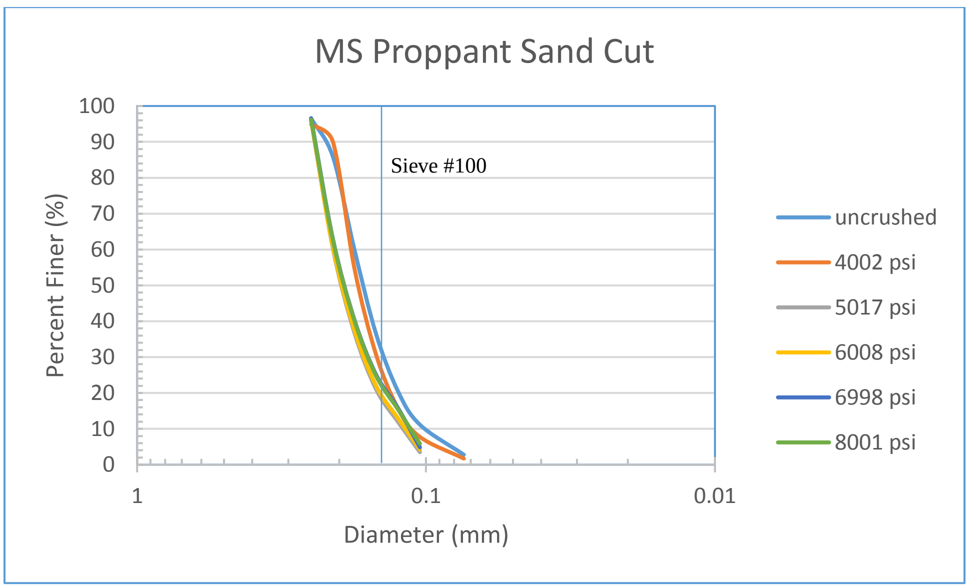

Figure 7b. Mississippi proppant sand sieve analysis cut (sieves 60-200)

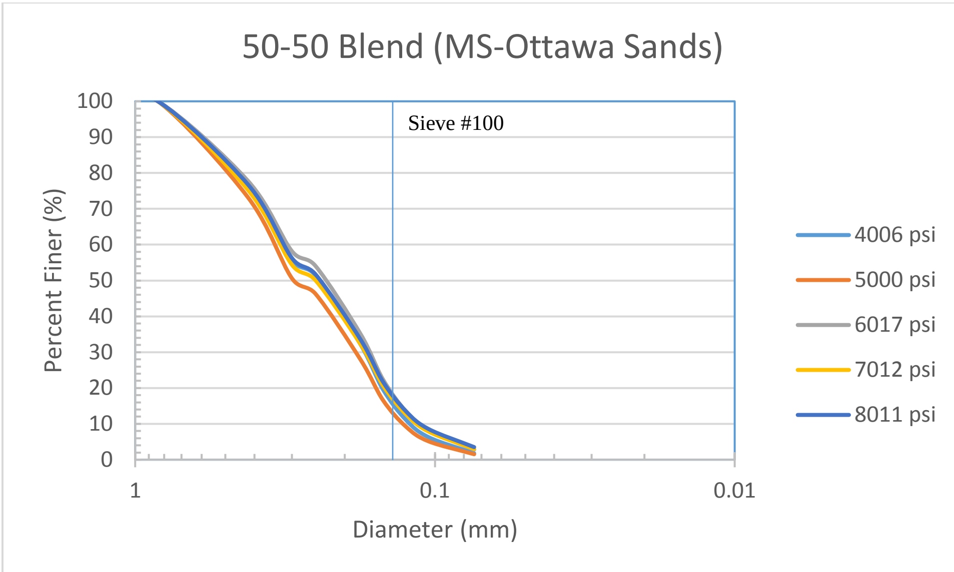

Figure 8a. 50-50 Blend sieve analysis

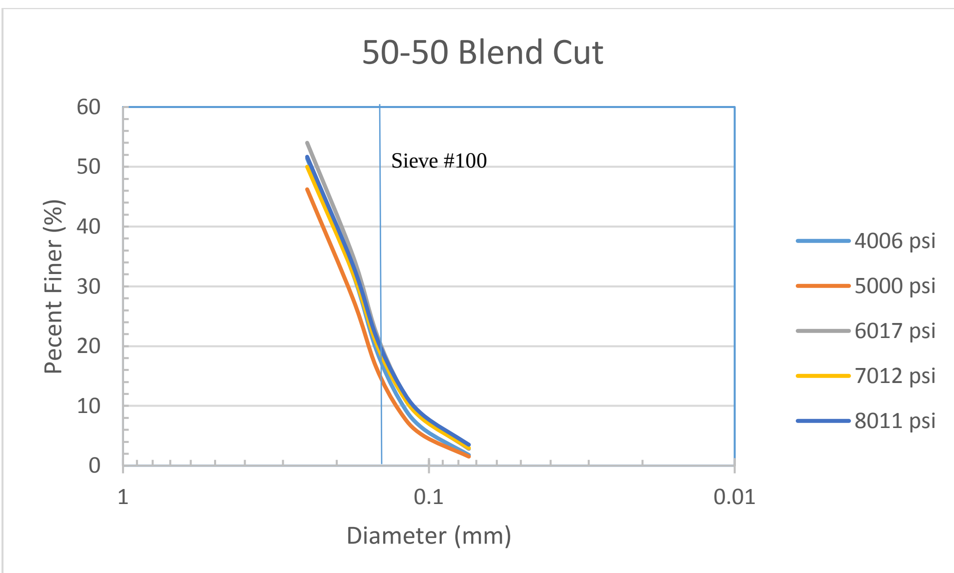

Figure 8b. 50-50 Blend sieve analysis cut (sieves 60-200)

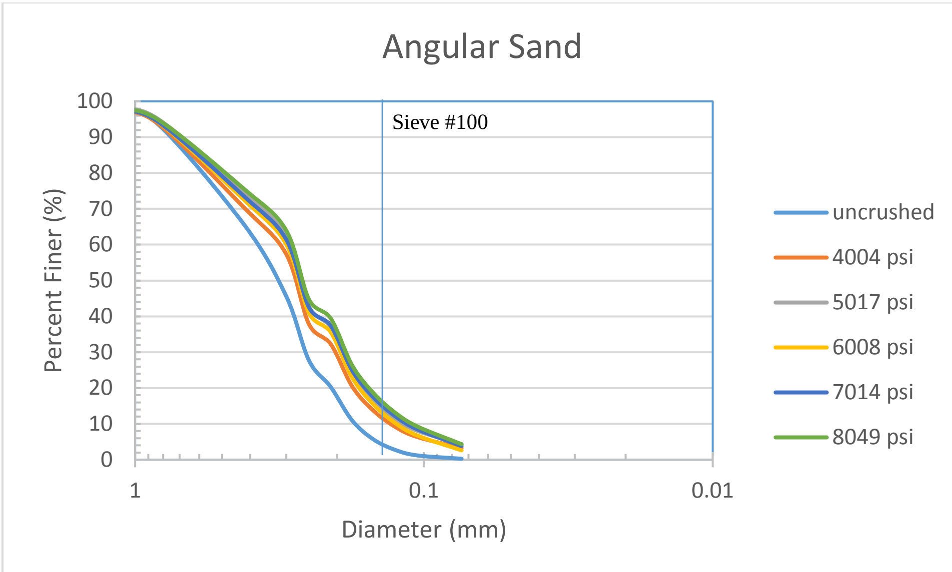

Figure 9a. Angular sand sieve analysis

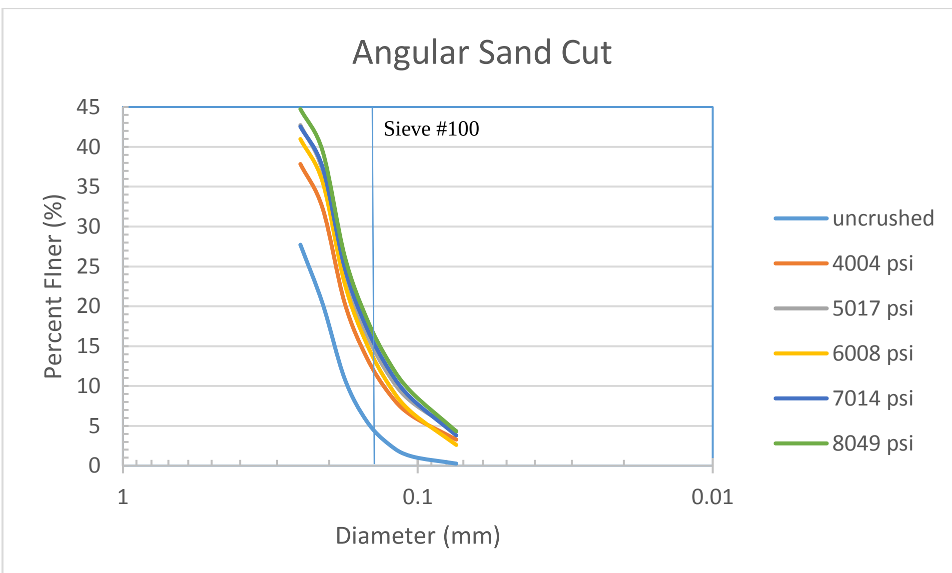

Figure 9b. Angular sand sieve analysis cut (sieves 60-200)

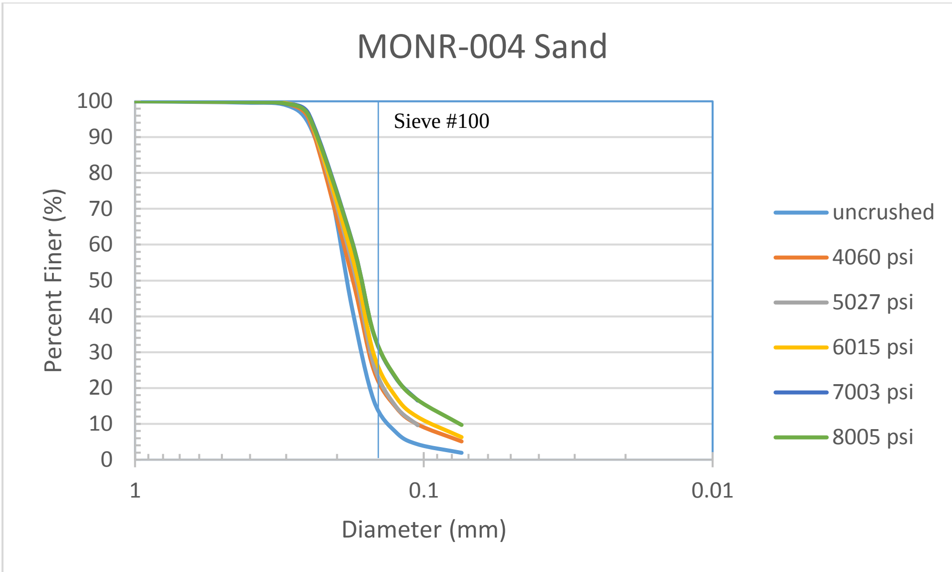

Figure 10a. MONR-004 sieve analysis

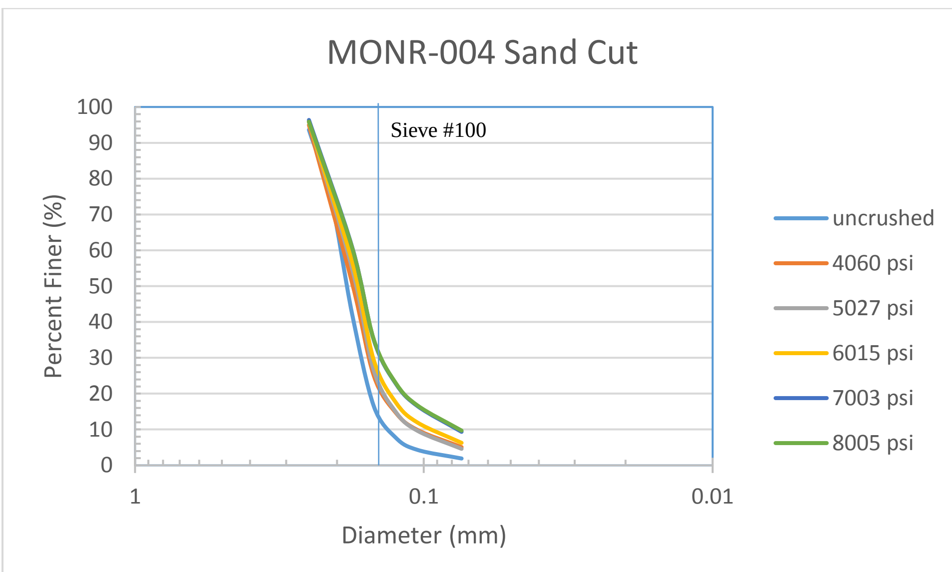

Figure 10b. MONR-004 sieve analysis cut (sieves 60-200)

Appendices

Appendix A: Sample Descriptions

Appendix B: Crush Test Sieve Analyses

Appendix C: Uncrushed Sample Sieve Analyses

Appendix A: Sample Descriptions

MO Proppant Sand: sand; 10YR 8/3 (very pale brown); fine-grained, well-rounded, well-sorted.

MS Proppant Sand: sand; 10YR 8/3 (very pale brown); fine- to very fine-grained, rounded, well-sorted.

Ottawa Sand: sand, white, medium- to fine-grained, well rounded, well sorted, quartz

Angular Sand: sand, tan, medium- to fine-grained with some coarse, angular, poorly sorted, quartz.

MONR-004: sand, micaceous; 7.5YR 7/4 (pink); fine- to very fine-grained, sub-angular, well-sorted with about 5% unidentified fine black mineral. Tuscaloosa Group outcrop in Monroe County, MS.

MONT-005: sand, micaceous, argillaceous; 10YR 8/6 (yellow); medium- to fine-grained, angular, moderately-sorted. Claiborne Group pit sample from Montgomery County, MS.

NOXU-001: sand; 10YR 8/4 (very pale brown); very fine- to medium-grained, sub-angular, poorly-sorted. Midway Group pit sample from Noxubee County, MS.

WINS-002: sand, micaceous; 10YR 7/8 (yellow); fine-grained, sub-angular to sub-rounded, poorly- to moderately-sorted. Claiborne Group pit sample from Winston County, MS.

Appendix B: Sieve Analyses

Ottawa Sand		% Finer					
Sieve #	D (mm)	0 psi	3998 psi	5000 psi	6001 psi	6992 psi	8002 psi
10	2.00	100.0	100.0	100.0	100.0	100.0	100.0
16	1.19	100.0	100.0	100.0	100.0	100.0	100.0
20	0.84	100.0	99.8	100.0	100.0	100.0	100.0
40	0.42	48.6	53.8	55.7	59.0	62.5	59.9
50	0.30	15.3	23.9	27.5	32.6	39.0	37.0
60	0.25	2.0	4.3	6.6	11.4	16.3	15.6
70	0.21	1.7	4.1	6.2	10.7	15.4	14.9
80	0.18	0.5	1.6	2.9	5.9	9.4	9.3
100	0.15	0.3	1.1	1.9	4.3	7.1	7.2
120	0.13	0.2	0.7	1.4	3.2	5.5	5.7
140	0.11	0.2	0.5	1.1	2.6	4.4	4. 7
200	0.07	0.1	0.2	0.7	1.6	2.8	3. 1

Figure B-1. Ottawa Sand sieve analysis

MS Proppant		% Finer					
Sieve #	D (mm)	0 psi	4002 psi	5017 psi	6008 psi	6998 psi	8001 psi
10	2.00	100.0	100.0	100.0	100.0	100.0	100.0
16	1.19	100.0	100.0	100.0	100.0	100.0	100.0
20	0.84	100.0	100.0	100.0	100.0	100.0	100.0
40	0.42	99.9	100	99.8	99.9	99.9	99.9
50	0.30	99.9	99. 8	99.6	99.6	99.7	99.6
60	0.25	96.6	94.9	96.2	96.0	96.6	96.2
70	0.21	85.8	90.0				
80	0.18	60.0	54.8	60.2	60.6	62. 9	62.6
100	0.15	36.5	30.7	36.8	37.6	40.4	40.2
120	0.13	20.4	15.6	21.1	22.0	25.1	24.8
140	0.11	11.1	7.7	11.9	12.9	15.8	15.4
200	0.07	2.8	1.7	3.5	4.2	4.8	5.8

Figure B-2. MS Proppant sieve analysis

MONR-004		% Finer					
Sieve #	D (mm)	0 psi	4060 psi	5027 psi	6015 psi	7003 psi	8005 psi
10	2.00	100.0	100.0	100.0	100.0	100.0	100.0
16	1.19	100.0	100.0	100.0	100.0	100.0	100.0
20	0.84	99.9	100.0	100.0	100.0	100.0	100.0
40	0.42	99.6	99.8	99.8	99.8	100.0	99.8
50	0.30	98.9	99.3	99.5	99.5	99.3	99.3
60	0.25	93.6	95.0	95.9	95.9	96.4	95.9
70	0.21	74.9					
80	0.18	42.1	50.8	54.8	56.8	60.8	60.7
100	0.15	16.5	25.0	26.5	29.3	35.0	35.1
120	0.13	7.7	14.7	14.9	17.5	22.8	22.9
140	0.11	4.3	9.8	9.6	11.9	16.5	16.7
200	0.07	1.9	5.1	4.6	6.3	9.4	7

Figure B-3. MONR-004 sieve analysis

Angular Sand		% Finer					
Sieve #	D (mm)	0 psi	4004 psi	5017 psi	6008 psi	7014 psi	8049 psi
10	2.00	99.7	99.8	99.7	99.8	99.6	99.7
16	1.19	98.0	97.7	98.2	97.9	97.8	98.1
20	0.84	93. 9	94.0	95.3	94.4	94.5	95.1
40	0.42	65.7	70.4	74.7	72.6	73.5	75.6
50	0.30	45.7	57.5	62.1	60.2	61.5	64.1
60	0.25	27.7	37.8	42.7	41.0	42.5	44.7
70	0.21	20.3	32.2	37.0	35. 6	37.4	39.4
80	0.18	10.9	20.4	24.2	22.9	24.9	26.3
100	0.15	5.6	13.6	16.5	15.3	17.3	18.5
120	0.13	2.7	9.1	11.3	10.1	12.0	13.0
140	0.11	1.2	6.3	8.01	6.7	8.4	9.2
200	0.07	0.3	3.3	4.3	2.6	3.8	4.3

Figure B-4. Angular sand sieve analysis

50-50 Blend		% Finer				
Sieve #	D (mm)	4006 psi	5000 psi	6017 psi	7012 psi	8011 psi
10	2.00	100.0	100.0	100.0	100.0	100.0
16	1.19	100.0	100.0	100.0	100.0	100.0
20	0.84	100.0	100.0	100.0	100.0	100.0
40	0.42	76.5	73.1	77.7	75.2	76.7
50	0.30	55.7	50.6	58.2	54.4	56.3
60	0.25	51.4	46.2	54.0	50.0	51.7
80	0.18	32.1	27.9	35.0	32.2	33.5
100	0.15	19.6	16.6	22.4	20.7	21.7
120	0.13	11.1	9.2	13.5	12.7	13.5
140	0.11	6.3	5.1	8.1	7.8	8.6
200	0.07	1.8	1.5	2.8	3.0	3.5

Figure B-5. 50-50 Blend sieve analysis

Sand	% Finer	psi
Ottawa	0.28	0
	1.06	3998
	1.94	5000
	4.29	6001
	7.07	6992
	7.21	8002
MS	36.5	0
	30.7	4002
	36.8	5017
	37.6	6008
	40.4	6998
	40.2	8001
50-50	19.6	4006
	16.6	5000
	22.4	6017
	20.7	7012
	21.7	8011
Angular	5.59	0
	13.6	4004
	16.5	5017
	15.3	6008
	17.3	7014
	18.5	8049
MONR-004	16.5	0
	25	4060
	26.5	5027
	29.3	6015
	35	7003
	35.1	8005

Figure B-6. Values of fines passing sieve #100

Appendix C: Uncrushed Sample Sieve Analyses

Sieve #	D (mm)	Sample (g)	% Retained	% Cumulative	% Finer
10	2.00	0	0	0	100.0
16	1.19	0.1	0	0	100.0
20	0.84	0.2	0	0	100.0
40	0.42	5.5	1.0	1.0	99.0
50	0.30	22.6	4.0	5.0	95.0
60	0.25	88.2	15.6	20.6	79.4
70	0.21	77.5	13.7	34.3	65.7
80	0.18	136.7	24.1	58.4	41.6
100	0.15	109.4	19.3	77.7	22.3
120	0.13	70.9	12.5	90.2	9.8
140	0.11	33.7	6.0	96.2	3.8
200	0.07	20.2	3.6	99.8	0.3
pan		1.4	0.3	100.0	0

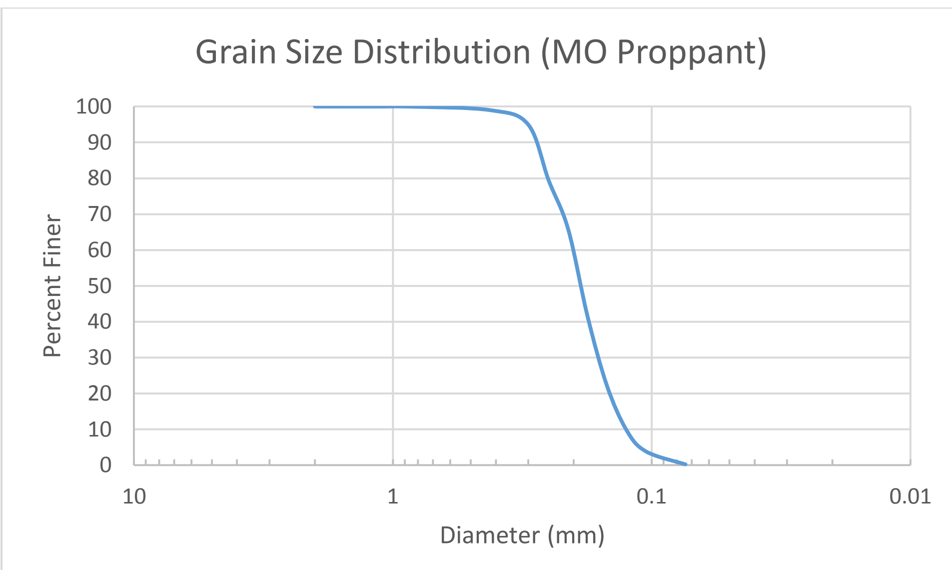

Figure C-1. Missouri proppant sand sieve analysis and grain size distribution chart

Sieve #	D (mm)	Sample (g)	% Retained	% Cumulative	% Finer
10	2	3.9	0.5	0.5	99.5
16	1.19	1.2	0.2	0.7	99.3
20	0.84	1.7	0.2	0.9	99.1
40	0.42	51.4	6.7	7.6	92.4
50	0.3	192.4	25.2	32.8	67.2
60	0.25	201.3	26.4	59.2	40.8
70	0.21	106.3	13.9	73.1	26.9
80	0.18	86.7	11.4	84.4	15.6
100	0.15	55.1	7.2	91.7	8.3
120	0.13	28.5	3.7	95.4	4.6
140	0.11	13.6	1.8	97.2	2.8
200	0.07	10.4	1.4	98.5	1.5
pan		11.3	1.5	100.0	0

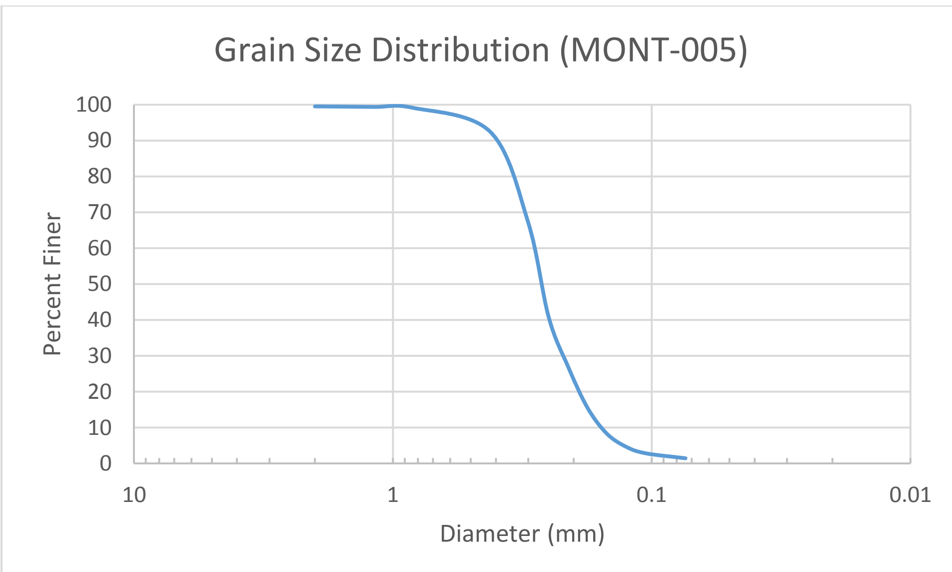

Figure C-2. MONT-005 sieve analysis and grain size distribution chart

Sieve #	D (mm)	Sample (g)	% Retained	% Cumulative	% Finer
10	2	0	0	0	100.0
16	1.19	0.5	0.1	0.1	99.9
20	0.84	3.2	0.5	0.5	99.5
40	0.42	73.0	10.5	11.1	88.9
50	0.3	215.9	31.2	42.3	57.7
60	0.25	202.4	29.2	71.5	28.5
70	0.21	55.8	8.1	79.6	20.4
80	0.18	35.6	5.1	84.7	15.3
100	0.15	17.9	2.6	87.3	12.7
120	0.13	11.5	1.7	89.0	11.0
140	0.11	8.9	1.3	90.2	9.8
200	0.07	13.8	2.0	92.2	7.8
pan		53.9	7.8	100.0	0

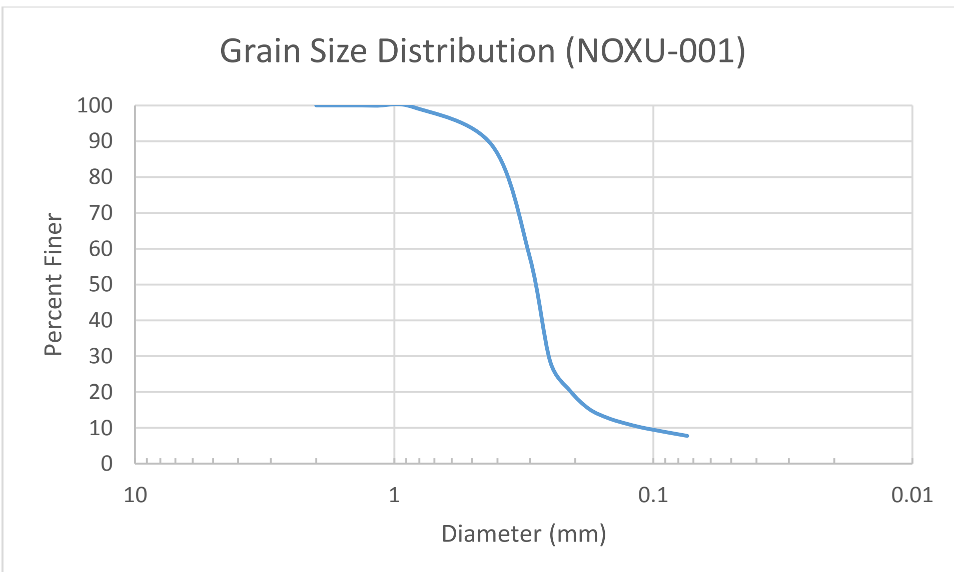

Figure C-3. NOXU-001 sieve analysis and grain size distribution chart

Sieve #	D (mm)	Sample (g)	% Retained	% Cumulative	% Finer
10	2	3.3	0.5	0.5	99.5
16	1.19	1.7	0.2	0.7	99.3
20	0.84	1.2	0.2	0.9	99.1
40	0.42	7.6	1.1	2.0	98.0
50	0.3	20.2	3.0	5.0	95.0
60	0.25	65.1	9.6	14.5	85.5
70	0.21	52.9	7.8	22.3	77.7
80	0.18	70.5	10.3	32.6	67.4
100	0.15	149.0	21.9	54.5	45.5
120	0.13	163.0	23.9	78.4	21.6
140	0.11	83.4	12.2	90.6	9.4
200	0.07	56.2	8.2	98.9	1.1
pan		7.7	1.1	100.0	0

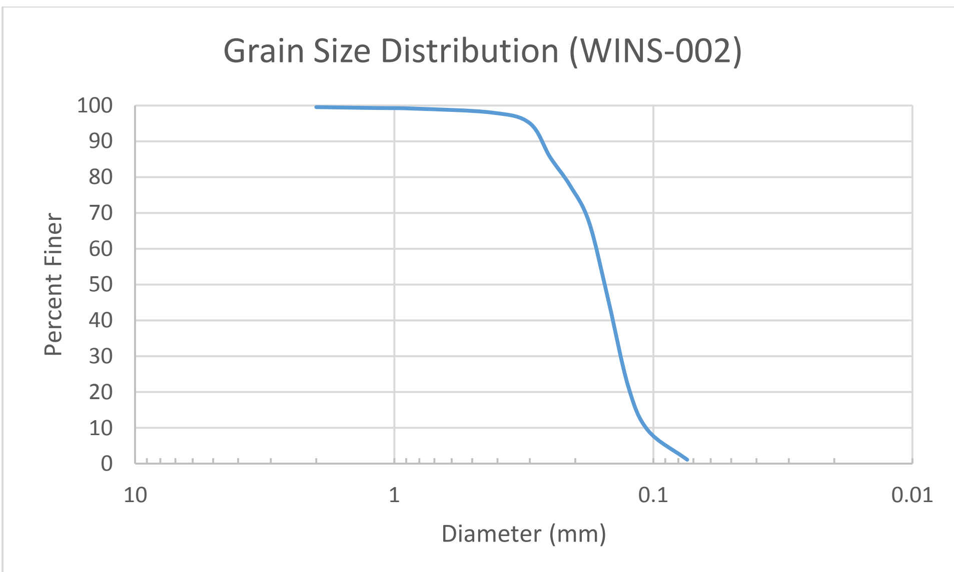

Figure C-4. WINS-002 sieve analysis and grain size distribution chart